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From natural driving to artificial intervention: Changes of the Yellow River estuary and delta development

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ABSTRACT

The estuarine delta of the Yellow River is a region of strong land-ocean-human interactions that undergoes a unique evolutionary process. In this paper, we combined historical data and remote sensing images to better understand the evolution of the Yellow River delta. Changes in the Yellow River estuarine flow path from natural swing to artificial diversion were first studied to understand the rules and mechanism of the delta formation. The complex geomorphic structural system of the Yellow River delta is constituted by contemporary and modern deltas and their sub-deltas. Remote sensing images and measured data indicate that variations in runoff and sediment load in the Yellow River estuary will affect the deltaic erosion and siltation. The natural and artificial factors that cause runoff and sediment changes include climate change, soil erosion control in the middle reaches, building reservoirs along the Yellow River, which are used as water supply for local cities and farmland irrigation, as well as the water and sediment regulation experiment in the Xiaolangdi reservoir. Furthermore, artificial intervention of diversion channels has contributed to the maintained stability of the Yellow River estuary environment, so as to have regional development and prosperity of the Yellow River delta.

1. Introduction

The estuary, an important part of a coastal zone, is an interface of land, atmosphere, and ocean systems (Olsen et al., 2009). In this key area of land-ocean interaction, the river carries sediment and nutrients into the sea, morphing the delta together with the ocean to enhance coastal biological productivity. Therefore, the estuary is always under the pressure of population growth, urbanisation, environmental pollution, and unsustainable over-exploitation (Dennison, 2008; Pasquaud et al., 2013). On the other hand, the estuary is also an environmentally active area, where the delta evolves due to land-ocean-human effects (Sun et al., 2016; Xu et al., 2016a,b). In the upgraded version of the longstanding Land Ocean Interactions in the Coastal Zone (LOICZ) project, Future Earth Coasts still lists the estuary as their key research area.

The Yellow River is the second longest river in China and the most sediment-filled big river on Earth.

As a river with the highest concentration of sediment (Lu et al., 2011), the sediment runoff and weak tide provide the Yellow River delta with unique estuary characteristics. Yellow River runoff sediment concentration reaches 25.3 kg/m^3, which is several to a hundred times the value of sediment concentrations in other well-known rivers, such as Colorado River (6.67 kg/m^3), Mississippi River (1.80 kg/m^3), Yangtze River (0.525 kg/m^3), Pearl River (0.29 kg/m^3), and Amazon River (0.156 kg/m^3). The Yellow River estuary also has typically weak tidal movement, where the tidal range is about 1.0 m and the tide velocity and flow are not large (Zhou et al., 2015). Due to the high sediment concentration and discharge, weak tidal movement, as well as small gradient of the Yellow River's estuary area, the sedimentation rate and delta extension speed are the greatest of those of the most well-known rivers in the world (Wang et al., 2017; Yu et al., 2013). Further, the deposition rate of the Yellow River delta is several times that of the Mississippi River Delta, more than 30 times that of the Yangtze River Delta, and more than 50 times that of the Pearl River Delta.

Furthermore, the wandering estuarine channel is a remarkable feature that influences the quick evolution process of the Yellow River estuary (Wang et al., 2016). The wandering channel of the Yellow River Estuary manifests in two aspects. First, the tail of Yellow River frequently bursts and changes; the second is that the river course and mouth are both wandering unstable forms with numerous branches,

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much water flow disorder, and a large wide-depth ratio, especially in the initial and final stages of diversion.

The objects of this study are: (1) To reveal the process of the evolution of the Yellow River estuary and the special rules of the delta formation; (2) To reflect the actions of natural and human factors in the evolutionary process. (3) To be a contribution to the research of the land-ocean-human interaction by a case study of the Yellow River estuarine region.

2. Study methods

2.1. Study area

The Yellow River has a total length of 5464 km and a catchment area of 795,000 km^2. It originates in the northern foot of the Bayan Har Mountains in the Qinghai-Tibet Plateau and flows through nine provinces of China. The middle section flows through the Loess Plateau, low section flows through North China Plain and into the Bohai Sea in Kenli, Shandong Province.

The Yellow River Estuary Delta refers to the delta formed by the alluvial deposit of the Yellow River after 1855, the year that the Yellow River burst at Tongwaxiang and began flowing into Bohai Sea from the watercourse of the Daqing River. The natural geographic delta has an area of about 6010 km^2, which contains the contemporary delta with the Ninghai as the apex and the modern delta with the Yuwa as the apex after the Yellow River's diverging point moved downstream in 1934. The administrative division includes most of Dongying City and the edge of Binzhou City in Shandong Province. The Yellow River Delta is rich in land, oil and gas, biological, marine, and warm temperate climate resources. However, the delta environment was unstable due to the swing of the Yellow River trail channel and its development was far behind other regions in earlier years. Later, the river course is relatively stable through manual intervention, and the delta has been developed (see Fig. 1).

2.2. Methods and materials

The research methods and materials used in this paper include the following parts:

(1) Historical data analysis. The historical data and related literature was collected analysed in this work to sort out the general understanding of the Yellow River estuary from the natural swing to artificial diversion process, and to map the sub-delta, contemporary delta and modern delta formation.

Table 1
Information of selected remote sensing images.
Source: www.rsgs.ac.cn; www.ceode.cas.cn; www.gscloud.cn

Terrestrial Satellite	Image type	Date
Landsat 5	MSS	Dec. 17, 1976
Landsat 5	MSS	June 5, 1985
Landsat 5	TM	May 31, 1996
Landsat 5	TM	Sep. 20, 1996
Landsat 7	ETM	Aug. 9, 2001
Landsat 5	TM	Apr. 28, 2007
Landsat 8	OLI	Oct. 5, 2013
Landsat 8	OLI	Oct. 3, 2018

Historical data used in this study include: Yellow River data and downstream river course changes from 1855 to 1988 (Yellow River Estuary Affairs Bureau of the Yellow River Conservancy Commission, 1995); measured data of the Lijin hydrological station of the Yellow River Estuary from 1950 to 2017; previous research and investigation reports (Gao et al., 1989; Science and Technology Commission of Shandong Province, 1991; etc.).

(2) Images analysis combining the measured figure.
A) Observed remote sensing images (MSS, TM, ETM, OLI) by the Landsat Terrestrial Satellite since 1976 year by year, the eight images which best reflect the evolution of the Yellow River delta are selected and explained to show the last two times Yellow River estuary changes after the planned diversion (see Table 1).

The above images contain system radiation and ground control point geometry corrections. The terrain correction was performed based on accurate ground control points and high-precision DEM data passes.

B) The measured average high tide line in 1980, 1991, 1993, 1996 and 2000 according to 28 sections established in the Yellow River Delta coast were mapped to show the siltation, erosion and relative stability of the delta coast.

(3) Natural and human factors analysis. The measured data of runoff and sediment discharge in the Lijin hydrological station of the Yellow River estuary from 1951 to 2017 were analysed to show the trend of water and sediment into the delta region, and then traced

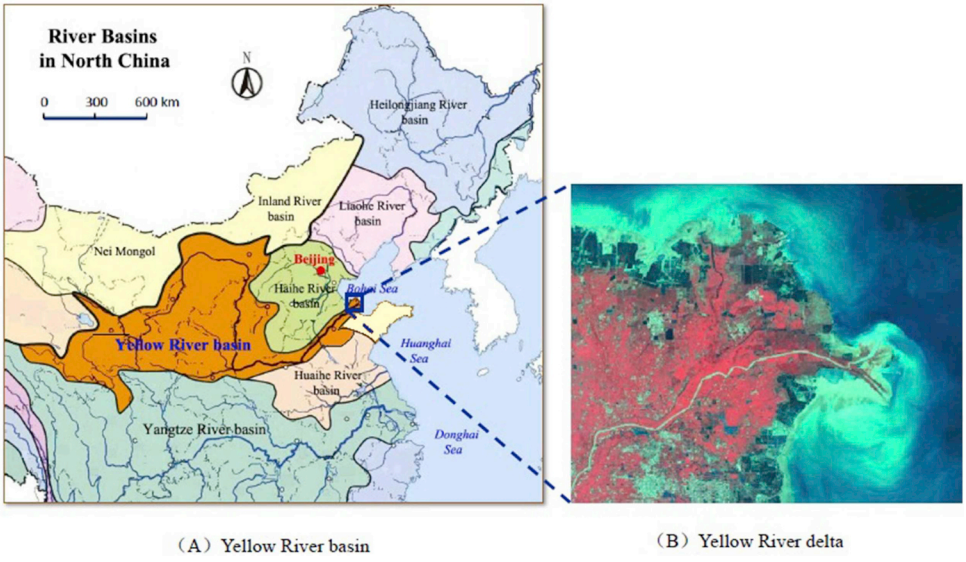

Fig. 1. Location of the study area (Source: The remote sensing images from www.rsgs.ac.cn).

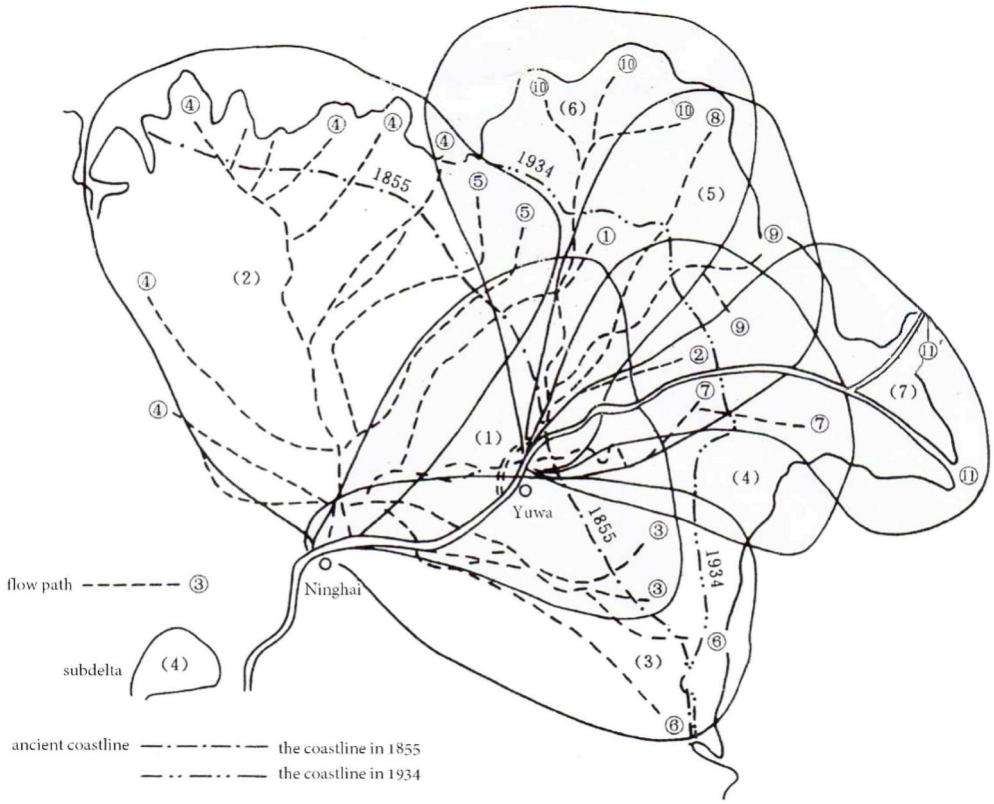

Fig. 2. Yellow River tail changes and delta system.

back to its natural and artificial reasons: mainly with attention to climate change, soil erosion control in the middle reaches, along the Yellow River building reservoirs and drawing off water irrigation, especially a typical example ——Xiaolangdi reservoir water and sediment regulation.

(4) Field investigation. The research team visited Dongying city located in Yellow River estuary on average every three years from 1990 to interview the government officers, business managers and citizens. The development plans for every five years were collected to understand the Yellow River Delta sustainable development path.

3. Results analysis

3.1. The processes of Yellow River flow path and the formation of delta

The Yellow River delta is an alluvial delta plain formed by siltation of the Yellow River. In 1855, the Yellow River busted into Tongwaxiang, Henan Province then changed its flow path towards the Daqinghe River course, which flows into the Bohai Sea from Xiaoshenmiao located in north of Tiemenguan, Lijin County. Since then, the Yellow River has flowed through the modern Yellow River delta for 152 years (from 1938 to 1947, the river flowed into the Yellow Sea from Jiangsu Province). As the Yellow River carries about 10.5×10^8 t sediment from the Loess Plateau to estuarial area, about two-thirds of sediment are transferred by the river silt up to the delta and coastal areas, while one-third is delivered inshore. The massive amount of sediment caused the Yellow River tail course to evolve following the rule: “Silting – Extension – River bed raising – Swing – Diversion”. The evolution stages of river tail appear periodically, shown as a small cycle. After each small cycle, a channel highland and estuary sandbar is stacked in the original flow path, while the next flow path is developed in the depressions on both sides. When the tail sweeps across the entire delta, a large cycle completes. Since 1855, the Yellow River burst and diverted more than 50 times, 10 of which were larger changes. Yellow River delta has experienced two large cycles. The Yellow River tail is always in the alternating erosion-siltation process, but mainly in siltation mode. Under the combined effect of water and sediment, river channel boundary conditions, and coastal dynamic elements, the entire coastline of the Yellow River delta advances an average of 0.16 km towards the sea each year, while the modern delta advances 0.23 km. Astonishingly, in the Qingshuigou course, the current flow path, the estuarine coastline advances an average of 1.8 km towards the sea each year, showing that the Yellow River delta is still extending.

The first cycle of the Yellow River tail evolution created the contemporary delta, and the second cycle created the modern delta. The contemporary delta consists of three sub-delta bodies, which were formed by six major diversion changes which vertex is Ninghai. The modern delta consists of four sub-delta bodies formed by five major diversion changes which vertex is Yuwa. The flow path changes in the delta and sub-deltas and previous major diversions of the Yellow River are shown in Fig. 2 and Table 2.

As Fig. 2 shows, the Yellow River tail natural swings following a certain rule: the flow path change starts in the middle axis (North-East), then moves to the left, then right, and finally back to the middle part. Artificial diversion makes this rule more complex. The range of the river's diversion gradually reduces as the vertex moves lower. Theoretically, a tail flow channel can form a sub-delta. However, the reality is that multiple flow paths can overlap and accumulate into a composite sub-delta body with a central axis. When a large cycle of the tail sweeps ended, the evolution of a delta is complete. Contemporary and modern delta and their sub-deltas constitute the Yellow River delta's geomorphic complex structure system (Gao et al., 1989; Ye, 1990; Xu, 1990; Science and Technology Commission of Shandong Province, 1991).

The Yellow River tail changes are displayed in Fig. 2, which shows that the tail wanders constantly. In the beginning, the main factor of the initial path change is natural swing, whereas the following three changes are mainly accountable to artificial diversion. In January 1964,

Table 2
Yellow River delta, sub-deltas, flow path changes and large diversion.

Delta (vertex)	Sub-delta (number, axis path)	Flow number	Flow period	Diversion time	Diversion reason
Contemporary delta (Ninghai)	(1) Yanwo - Xiaoshenmiao	①	1855.8–1889.4	1855.6	Burst in summer flood
		②	1889.4–1897.6	1889.3	Burst in ice flood
		③	1897.6–1904.7	1897.6	Burst in summer flood
	(2) Yanwo - Taipingzhen	④	1904.7–1926.7	1904.7	Burst in summer flood
		⑤	1926.7–1929.9	1926.7	Burst in summer flood
	(3) Ninghai - Xishuanghe	⑥	1929.9–1934.9	1929.9	Artificial diversion
Modern delta (Yuwa)	(4) Tianshuigou	⑦	1934.9–1938.7	1934.9	Artificial blocking flood but not closed
		⑧	1947.3–1953.7	1947.3	Artificial diversion in Huayuankou
	(5) Shengxiangou	⑨	1953.7–1964.1	1953.7	Artificial diversion
	(6) Diaokouhe	⑩	1964.1–1976.5	1964.1	Artificial diversion in ice flood
	(7) Qingshuigou	⑪	1976.5–1996.6	1976.5	Artificial diversion
	(7) Branch of Qingshuigou	⑪’	1996.6～now	1996.6	Artificial open a branch

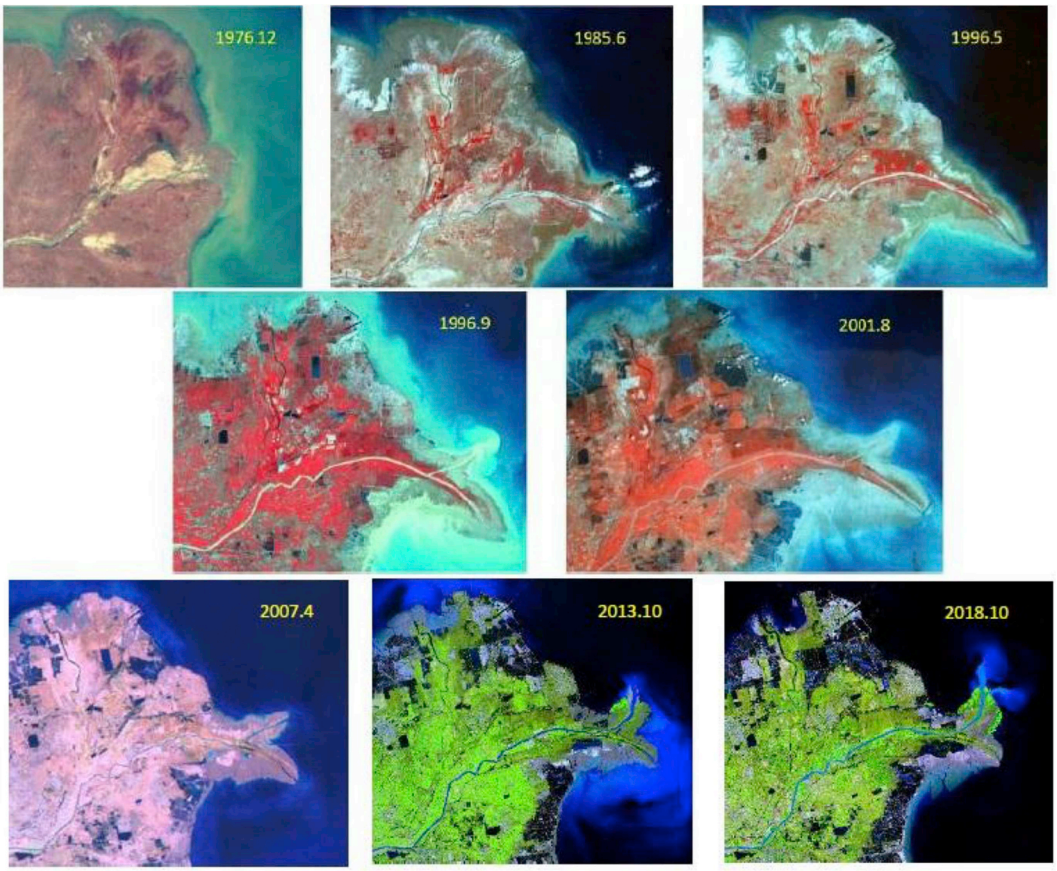

Fig. 3. Changes in the Yellow River Estuary from 1976 to 2018 (Source: The remote sensing image obtained from www.rsgs.ac.cn). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the flow path changed towards Diaokouhe branch because of a designed embankment blasting in Luojiawuzi. In May 1976, the formation of the Qingshuigou branch occurred due to artificial diversion. In 1996, the Qing 8 man-made river branch opened.

3.2. Evolution of the Yellow River delta

The remote sensing images were used to monitor estuarine changes since the late 1970s, from which we see 2 artificial diversion and different typical evolution stages. There are 8 images in Fig. 3. (1) The 1976 image of the Yellow River tail shows a change just from the Diaokouhe flow path to the Qingshuigou flow path via human effects. (2) In June 1985, the estuary protruded outward. (3) In 1996, the estuary was like beak-shaped. (4) In June 1996, the north branch opened in Qing-8 Section, within three months from June to September a new thumb-shaped estuary silted out. (5) The image of August 2001, during past 5 years, the Yellow River had been interrupted for a long time, so the speed of estuary extension was hindered. (6) In April 2007, the new estuary was obviously silted up due to the water and sediment regulation experiment in the Xiaolangdi Reservoir carried out since 2002. During this experiment, the sediment containing much silt was transferred by floods, some of which was silted in the estuary. Meanwhile, the original estuary was eroded because of the lack of sediment replenishment. (7) In October 2013, the new estuary became the main part instead of the original one. (8) In October 2018, the new estuary deposited more outward. From January to October, there was water runoff $311.99\times10^8\ m^3$ and sediment discharge $2.93\times10^8 t$ flowed into this estuary, but the original estuary was eroded more short due to no

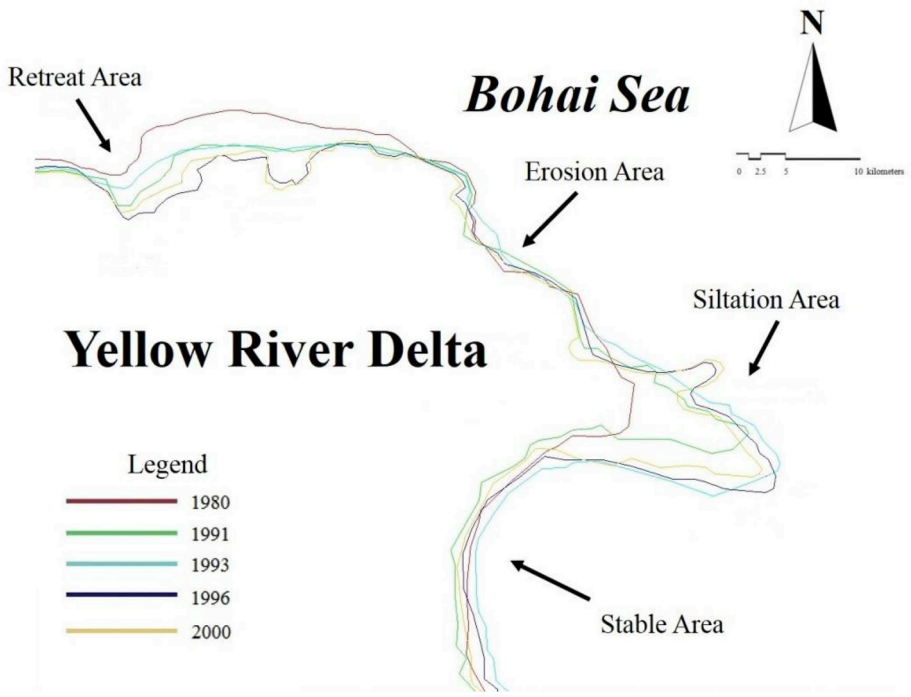

Fig. 4. Coastlines of Yellow River delta in 1980, 1991, 1993, 1996 and 2000 (Source: Yiji Cheng, 2016[1]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sediment replenishment.

Fig. 4 is a measured map of the Yellow River delta that shows the coastlines in 1980, 1991, 1993, 1996 and 2000, and displays siltation area, stable area and erosion areas.

Since 1855, a total of 2708 km^2 of new land has been deposited in the Yellow River delta. Before the 1980s, about 1.2 billion tons of sediment was deposited in the delta and coastal areas, making advancing the region towards the Bohai Sea an average of 1.5–3 km per year, and about 26.7 km^2 annually. From 1976 to 1999, after artificial diversion of the tail, the area of new land reached 323 km^2, an average annual of 14.0 km^2. After 1999, the area of the delta decreased continuously with the areas of erosion more than siltation.

3.3. Natural and human impact factors

The siltation of the estuary is directly related to the incoming water and sediment. Fig. 5 displays the annual runoff change at the Lijin Hydrology Station in the Yellow River estuary from 1950 to 2017. The general trend shows a decrease in the volume of water, especially in the late. After 2000, the Yellow River no longer stops flow due to water regulation in the upper reaches. Fig. 6 displays the annual sediment discharge changes in the same hydrology station.

In the figures shown above, the average amount of incoming water and sediment were reduced from 1950 to 2017, which is accountable to identified natural and human factors. Natural influences are related to the reduction of precipitation and runoff due to climate change. Human impact include that construction of reservoirs in the upper reaches, soil and water conservation program, irrigation, and domestic water increase account for the artificial factors (Wang et al., 2016, 2017). Although human regulation has caused an increase in the amount of incoming water from 2001 to 2017, the average amount of sand is still decreasing due to the soil and water conservation program in the basin (Kong et al., 2015, 2016). The period of Yellow River flow path is longer.

Xiaolangdi Dam reservoir's water and sediment regulation is a typical example (see Fig. 7). Xiaolangdi reservoir is located at the juncture of the middle and lower reaches of the Yellow River. Before flood season, in Xiaolangdi reservoir, the huge amount of water are released, carrying sediment at reservoir bottom to form density flow, and alluvial river channel of the Yellow River, wash away river sediment to the estuary, so to clean up the river channel and deposit a new land. During the period of water and sediment regulation, the average flow rate of Lijin station was 2167.6 m^3/s, which is 3.97 times the average annual flow rate. The average water level of Lijin station was 12.6 m, which is 1.36 m higher than the average annual water level.

The estuary, where the Yellow River flows into sea with sediment, was the siltation area because of the oriented land effect. After diversion, there is no sediment supplement in the erosion area and the ocean effect is oriented. The coastline maintains stability in the area where there is a balance land-ocean effect. The North Branch silted up quickly, while sediment regulation occurs in the Xiaolangdi Reservoir (Hu et al., 2015; Bi et al., 2014). Considering that the latter effect is deemed a human factor of estuary formation, the evolution of the Yellow River estuary reflects the interaction of land, ocean, and humans, or the "land-ocean-human effect".

3.4. Development of Yellow River Delta

The Yellow River delta is the most active area of ocean and land change in China and the world's largest river delta (Ottinger et al., 2013). It has advantageous geographical location, vast land, and rich resources. In history, frequent changes of the Yellow River tail make the environment extremely unstable, limiting development of the delta. Yellow River tail has burst, swung, and diverted in history without any regulation due to technical and financial reasons; thus, the delta has suffered from floods, ice floods, droughts, salinization, surges, and other nature disasters. Because industrial and agricultural production cannot proceed under unstable conditions, the Yellow River delta has always been very desolate compared to other rivers deltas that are bustling metropolises in sharp contrast. The construction of the Shengli

[1] Yiji Cheng, 2016. The variation of water and sediment flux and the response of the relevant factors in the Yellow River Estuary (Report).

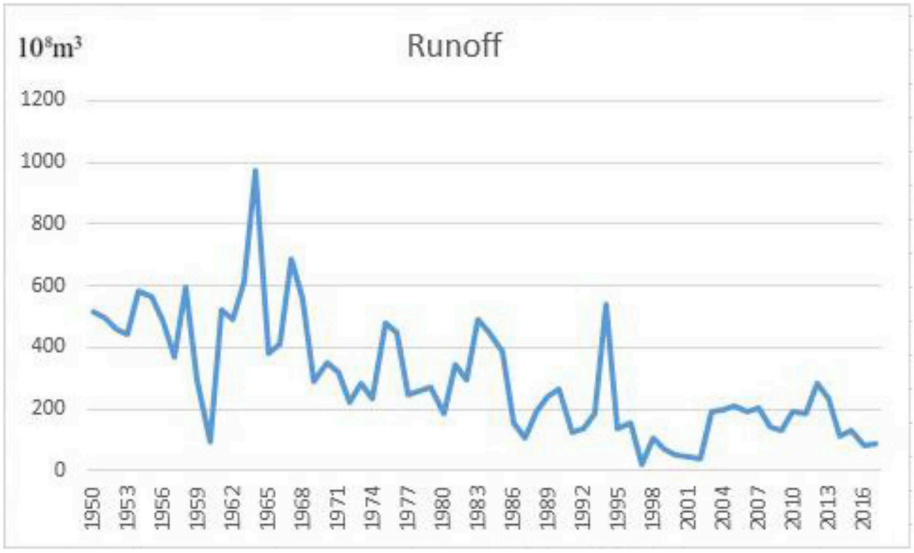

Fig. 5. Runoff changes in Lijin Hydrology Station from 1950 to 2017.

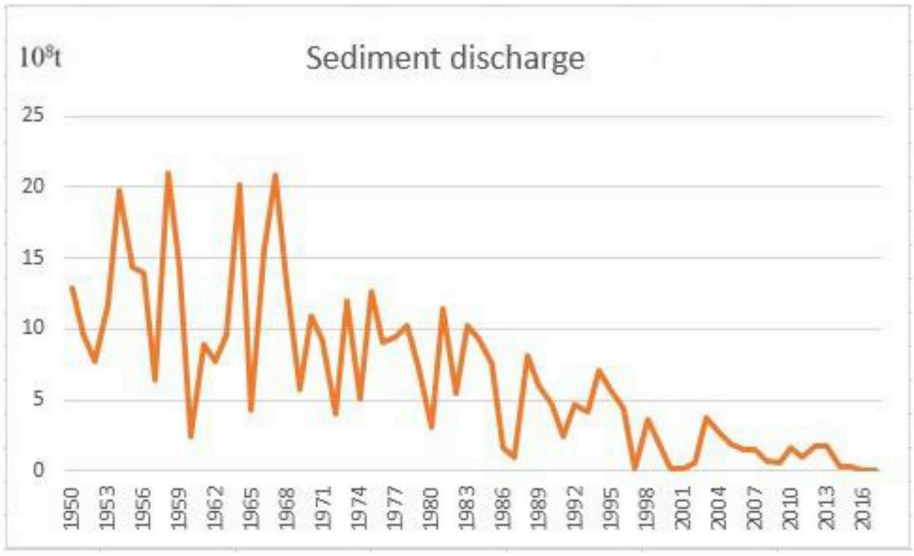

Fig. 6. Sediment discharge changes in Lijin Hydrology Station from 1950 to 2017.

Fig. 7. Xiaolangdi Reservoir's water and sediment regulation.

Oil Field in the 1960s promoted the development of the delta through the artificial control and intervention of the diversion of the flow path (Kuenzer et al., 2014). In the case of the oil fields, the Yellow River Conservancy Commission and the relevant departments carried out an artificial diversion without flooding in 1976 to prevent the heavy losses caused by the natural diversion. The non-flood diversion of the

Qingshuigou flow branch in the Yellow River was a successfully planned diversion. Planned diversion has allowed for control of the Yellow River tail and promotes the stability of the delta environment. After the 1976 diversion of the North Branch flow, the water has been stable for 42 years. The Yellow River delta's development started from oil exploitation in 1964, the Dongying City was set up in 1983. The Yellow River delta is also a significant grain and cotton production base. In the main part of the delta, groundwater has high salinity and is difficult to use for production, thus the Yellow River is an important source of fresh water. The estuary management, economic development, and environmental protection are the main backbones for sustainable development of the delta.

The development goals of Yellow River delta are: effective ecological economy, protection and restoration of wetlands, and the long-term stability of the Yellow River estuary. These are explained in more detail below.

(1) Besides this is the country's second largest oil industrial base and agricultural base, the beaches and bare lands in the Yellow River delta can be used for salt fields or aquaculture for shrimp, sea cucumber, fish, and crab for instance. The “Yellow River Crab” has become a well-known brand.
(2) There are large areas of young estuarine wetlands. A national nature reserve was established in 1992, which is aimed to protect the wetland ecosystems and rare birds. There are 393 kinds of plants and 367 kinds of birds in this reserve; 12 species of birds are national level first-class protected animals and 51 species are second-class protected birds.
(3) Long-term stability of the Yellow River estuary is the foundation of regional sustainable development. To achieve this goal, water and sediment control, flood discharge capacity, seawall building, and erosion prevention are all important methods of estuary management.

4. Discussion

The current Qingshuigou flow path in the Yellow River Estuary has been stable for more than 40 years, which is an important prerequisite for the development and prosperity of the delta. However, swinging and diverting are all manifestations of the estuary as a means to obtain the least resistance flow path. Each time a diversion is made, the flow path is shortened, the erosion reference plane is moved inward, and the water level in the estuary is significantly reduced. Generally, headwater erosion is generated and subsequently improves the downstream riverway, which is a natural law that we cannot ignore. In fact, the stability of the Qingshuigou flow path is achieved by implementing a partial small diversion under the premise of moving the swing point down river, including several small subdivisions, such as the distributary channel. According to the characteristics of the Yellow River and the objective law of estuary evolution, it is also necessary to plan a large-scale artificial diversion during the non-flood season.

On the other hand, since the Yellow River was diverted to the Qingshuigou flow path, the sub-delta of the original Diaokouhe River course has been strongly eroded. There are not sediment replenished for a long time in this area, and the seawall has been hollowed out. The erosion has also negatively affected exploitation of the oil fields, which used to sit in silting-up land but are now in a shallow sea.

Therefore, it is necessary to preserve the Diaokouhe River course in the delta area as an alternative flow path for the Yellow River diversion. The local government is planning to use the Qingshuigou and Diaokouhe flow paths alternately to obtain long-term stability of the delta environment.

In short, the problem of the Yellow River Estuary flow path is an integral part of the entire Yellow River governance. From the perspective of large systems, the issue of siltation in the downstream area and estuary can be solved by preventing soil erosion in the middle and upper reaches of the river and reducing the sources of sediment, which have shown to have remarkable effects thus far. According to the objective laws, the delta area of the Yellow River's trail flow path is relatively stable, yet instability is inevitable. In order to stabilize the environment of the delta for a long time and achieve sustainable development of the region, it is necessary to consider how to stabilize the current flow path for many years to come and to seek a systematically controlled and systematic change that conforms to the characteristics of the Yellow River and laws of nature. This also reflects the interactions of land (river dynamics and land formation by sedimentation), ocean (ocean power and erosion), and humans (various management measures and flow path control) in the delta.

5. Conclusions

The Yellow River is the second largest river in China and possesses an extremely high sediment concentration, which plays an important role in the evolution of the Yellow River delta. The Yellow River estuary is influenced by land-ocean-human interactions, showing a unique evolutionary rule. In this work, historical data analysis, images analysis and measured figure analysis were used to reveal the rules of Yellow River estuary evolution. The results of this study are as follows: (1) The diversion of the tail of the Yellow River has a certain regularity, which starts from the middle axis, swings to the left first then to the right, and finally back the middle, forming a cycle. Each flow path forms a sub-delta, a cycle will complete the evolution of a delta. Contemporary and modern deltas' form process has been associated with estuary natural swing to artificial diversion. (2) The variation of runoff and sediment in the Yellow River affects the siltation and erosion of the delta. Yet the natural and artificial reasons of runoff and sediment changes and decrease include that climate change, soil erosion control in the middle reaches, along the Yellow River building reservoirs and drawing off water supply city and irrigation, Xiaolangdi reservoir water and sediment regulation, and so on. (3) The artificial control of the Yellow River tail allows the stability of the delta to be maintained, which offers promising potential for future development and prosperity of the delta. The tail paths still need to be management according to rules, to achieve the estuarine regional sustainable development.

Yellow River governance is a significant affair in China concerning about one hundred million people. From upstream to downstream, each part of the river has its unique environment problems which constitute a systematic issue. In this research, the rules of Yellow River estuary changes were reported. The Yellow River estuarine evolution is not only a unique high sediment concentration river's characteristic, but also an effect of land-ocean-human interaction.

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